Journal of Healthy Eating and Active Living
2026, Vol. 6, No. 1, pgs. 41-62

Association between walkability and diverse health metrics: moderating role of social vulnerability

Farnaz Hesam Shariati[1], Anna L. Chupak[1], Erin Looney[1], Shirelle H. Hallum[1], Courtney M. Monroe[1], Mojtaba Kazemian[2], and Andrew T. Kaczynski[1,3]

[1] Department of Health Promotion, Education, and Behavior, Arnold School of Public Health, University of South Carolina, U.S.A.

[2] Department of Health Services Policy and Management, Arnold School of Public Health, University of South Carolina, U.S.A.

[3] Prevention Research Center, Arnold School of Public Health, University of South Carolina, U.S.A.

Abstract:

Little research has considered associations between walkability and multiple health outcomes and the moderating effect of social determinants of health. This study examined relationships between walkability and diverse health issues (depression, poor mental health, poor physical health, mobility disability, obesity) and no leisure-time physical activity and whether these relationships were moderated by social vulnerability. Then, we assessed whether these moderated effects varied between urbanicity. For 1089 census tracts in South Carolina, we compiled EPA National Walkability Index, 6 health metrics from the CDC-PLACES dataset, and the CDC Social Vulnerability Index. Multilevel regression models were employed to account for the nested structure of the data, with census tracts (level 1) nested within counties (level 2). Overall, tract walkability was significantly negatively associated with poor mental health, poor physical health, obesity, and no leisure-time physical activity. The interaction between National Walkability Index and Social Vulnerability Index suggested that the relationship between health metrics and walkability varied depending on the level of social vulnerability in the community. In addition, tract rural or urban classification significantly altered the relationship between walkability and some health metrics. This study's findings provide valuable insights for equitable urban planning and strategies to address walkability and public health issues.

Keywords: health risk behavior; mental health; physical health; public health; social vulnerability; walkability

The prevalence of physical and mental health issues has risen significantly in the United States (US) in recent years compared to past decades (Twenge et al., 2019). Conditions such as poor mental health, poor physical health, and physical inactivity are among the leading contributors to chronic diseases like obesity and depression (Anderson & Durstine, 2019; Booth et al., 2017; Harris, 2018, Kocjan et al., 2024; Ohrnberger et al., 2017; National Heart, Lung, and Blood Institute, 2022). Currently, nearly 40% of US adults are classified as obese, 8.3% have major depression, and the prevalence of physical inactivity is 25.3%, all risk factors that are linked to severe and often fatal outcomes such as heart attacks and strokes (Centers for Disease Control and Prevention [CDC], 2024; National Institute of Mental Health, 2021; CDC, 2024e; Kurth et al., 2002; Lavie et al., 2019; Pan et al., 2011; Penninx et al., 2001; Powell-Wiley et al., 2021; Sher et al., 2010; Willey et al., 2017). Given the prevalence of these concerns, there is an urgent need to tackle these issues upstream and to consider the relation of neighborhood factors such as walkability with diverse physical and mental health outcomes.

Indeed, historically, much research has focused on individual-level risk factors, whether behavioral or biological, often without considering the environments or social contexts that facilitated their emergence and persistence (Diez-Roux, 2003). While this approach has yielded valuable insights into personal determinants of health, it overlooks the systemic and structural factors that shape individual behaviors and health risks (Brown et al., 2019; Link & Phelan, 1995). One of these structural level factors is neighborhood infrastructure and accessibility to health-promoting environments (Tao et al., 2022). For instance, living in neighborhoods with limited access to green spaces, poorly maintained sidewalks, or high crime rates can constrain opportunities for physical activity and increase stress levels, both of which are significant contributors to physical and mental health problems (Foster & Giles-Corti, 2008; Lauwers et al., 2021; Rees-Punia et al., 2018; Salvo et al., 2018). Such narrow approaches fail to account for the diverse physical and social characteristics of neighborhoods, which play a critical role in shaping individual health outcomes relevant to such health outcomes (Diez-Roux, 2007, 2016; Diez-Roux et al., 2017).

Researchers have recently begun to focus on assessing the effects of spatial context and factors at the neighborhood level on residents' health as an upstream solution (Diez-Roux, 2007; Diez-Roux & Mair, 2010; Macintyre et al., 2002). This shift underscores the importance of designing healthy communities, which is a crucial step in mitigating physical and mental health problems (Kumar & Preetha, 2012; Sallis et al., 2012). In particular, the walkability of neighborhoods, as one key component of a built environment, can affect how well individuals' health outcomes are addressed at the population level (Kaczynski, 2010; Laddu et al., 2021). Neighborhood walkability can be defined as the extent to which the features of the built environment allow residents to travel to work or walk for leisure, exercise, and access to services (Kaczynski et al., 2012; Leslie et al., 2007). Walkability is often determined by factors such as mixed land use, street connectivity (i.e., pedestrian-friendly grid-like street network), and net residential density (i.e., population density), enabling people to engage in active transportation on a daily basis safely (Wei et al., 2016; Lovasi et al., 2011; Thomas et al., 2025). Considering a neighborhood's walkability is crucial because walkable spaces facilitate low or no-cost physical activity, such as walking, jogging, or cycling, which require minimal equipment or financial investment (McCormack et al., 2022). Also, engaging in physical activity regularly is associated with decreasing the global burden of chronic diseases (Anderson & Durstine, 2019). Other research has also documented the favorable relationship between increased walkability and important social and mental health factors, such as social capital, social isolation, and depression (Asiamah et al., 2023; Leyden, 2003; Mazumdar et al., 2018).

Given its significant role in promoting diverse aspects of community well-being, access to walkable environments may be considered a social determinant of health (Westenhöfer et al., 2023). Unfortunately, some research suggests that walkable environments are not always equitably available within and across communities (Bereitschaft, 2017; Pereira et al., 2023). For example, in the San Francisco Bay area, Riggs found that black residents lived in less walkable neighborhoods (Riggs, 2016). Although such research has shed light on disparities in walkable environments, a more holistic means by which to address environmental justice issues is to consider the construct of social vulnerability. Social vulnerability is defined as the likelihood of a particular population being adversely affected by hazards, such as those related to environmental or health issues (Andrew, 2015; Mah et al., 2023). It is comprised of several measures related to sociodemographic factors, population density, and transportation, and may shape mobility patterns and active transportation (Gordon-Larsen et al., 2006; Hansmann et al., 2022; Riggs & Sethi, 2020). A number of studies have examined the role of social vulnerability in this regard. For instance, one study by Wali (2023) showed that neighborhoods with high walkability and low social vulnerability had about 20% lower COVID-19 mortality rates compared to those with low walkability and high social vulnerability. In addition, another study assessed the association between residential county social vulnerability and leisure-time physical inactivity among US adults, and found that compared to people living in counties in the least vulnerable areas, those living in the mid-low, mid-high, and highest social vulnerability quartiles had higher odds of being physically inactive during leisure time (An & Xiang, 2015). Another study by Bereitschaft (2023) also investigated whether socially vulnerable populations had equitable access to walkable and transit-accessible neighborhoods within America's largest metropolitan areas founding a lower transit accessibility for high socially vulnerable populations living in more walkable neighborhood. Given these previous findings, we deemed it important to examine the role of social vulnerability moderating the relationship between walkability and health. For example, greater walkability may be significantly associated with health in more vulnerable neighborhoods that lack transportation or other individual or

environmental assets, but little research has explored such issues to date.

In addition to differences by social vulnerability, the relationship between walkability and health may also vary in urban versus rural contexts (Fan et al., 2017). For example, one study found that among urban youth, higher Walk Scores were linked to higher body mass index (BMI) z-scores, while among rural youth, higher Walk Scores were linked to lower BMI z-scores (Stowe et al., 2019). Likewise, a study of older adults reported that those residing in more accessible environments, such as areas with continuous barrier-free sidewalks and nearby public transportation, had 18% higher odds of belonging to the more mobile group (Clarke & Gallagher, 2013). In contrast, a few studies found no differences in the relationship between walkability and health by urban-rural categories (Bucko et al., 2021; Kasehagen et al., 2012). Such variation in literature suggests the importance of considering urbanicity in such an analysis as a stratifying variable. Multiple studies in a similar scope have used Rural-Urban Commuting Area (RUCA) codes to stratify their study settings into urban-rural categories (Adams et al., 2025; Kasehagen et al., 2012; Makram et al., 2025). Thus, we employed the same approach, stratifying our census tracts into urban and rural categories using RUCA codes to better understand differences in how walkability relates to health outcomes in different types of environments (U.S. Department of Agriculture, Economic Research Service, 2025).

In summary, while diverse studies have reported a relationship between walkability and health, several important gaps remain in this research area. First, many studies focus on the association between walkability and a single health outcome or behavior (e.g., physical activity), but not multiple health issues concurrently. Second, little research has considered the moderating effect of social determinants of health, especially using a composite metric such as social vulnerability (Edwards & Dulai, 2018; Reis et al., 2013; Van Holle et al., 2014; Bereitschaft, 2017). Third, minimal research about walkability and health, including variations by vulnerability, has been conducted within the Southeastern US where disparities in environmental justice and health equity are substantial (Bereitschaft, 2017, 2023; Bernhart et al., 2022). Finally, key differences may exist in the association between walkability and health in rural versus urban areas, but this has rarely been considered (Stowe et al., 2019). Given these limitations, the overall purpose of this study was to conduct an equity analysis regarding walkability and its association with diverse health issues related to mental and physical health (i.e., depression, poor mental health, poor physical health, mobility disability, obesity, no leisure-time physical activity) across all census tracts in South Carolina (SC). In particular, we sought to answer the following research questions:

1. What is the relationship between walkability and the aforementioned health issues and behaviors?
2. Is the relationship between walkability and these health issues and behaviors moderated by social vulnerability?
3. Is the relationship between walkability and these health issues and behaviors moderated by social vulnerability different in urban versus rural areas?

The state of SC provides a valuable setting in which to investigate such issues for multiple reasons. First, SC demonstrates considerable variation in social vulnerability, which makes it a preferable study setting to closely study how structural and sociodemographic factors might influence the links between walkability and health outcomes (Sonawane et al., 2024). Second, the state faces significant health challenges, such as high rates of obesity, physical inactivity, and chronic disease (America's Health Rankings, 2021). Finally, walkability across SC varies widely and has not been prioritized in most community planning efforts. Therefore, these considerations make it especially important to study how walkable environments affect health in this area.

Overall, a better appreciation of walkability and health outcomes and their variations by social vulnerability and urbanicity/rurality can provide valuable insights and compelling evidence for policymakers and planners to tailor interventions and design strategies to address the unique health challenges faced by communities in SC.

Methods

Study Setting

This study examined all census tracts within SC (n=1103). Census tracts were chosen as the geographic unit of analysis in this study because they are widely used in public health and urban planning research, offering standardized and consistent boundaries for linking environmental and sociodemographic data. Unlike considering buffer zones which focus on individualized spatial contexts, census tracts allow for regional comparisons and facilitate integration with existing datasets such as social vulnerability and various health outcomes. The estimated land area of included tracts was approximately 30,064.28 square miles with a population of 5,118,425 (US Census Bureau, South Carolina, 2020). Approximately 1 in 4 residents (26.0%) in SC identified as African American and 69.0% as White (US Census Bureau, South Carolina, 2020). In addition, 19.3% of the total population was 65 years or older, while 21.3% was 18 years or younger. The median household income in 2022 was $63,623, and 13.9% of the population lived in poverty (US Census Bureau, South Carolina, 2020).

Study Design

This study used a cross-sectional design to analyze the association between neighborhood walkability and health.

Measures

Neighborhood Walkability

To measure the walkability of neighborhoods, the US Environmental Protection Agency (EPA) created the National Walkability Index to assign census block groups a score from 1 (least walkable) to 20 (most walkable) (J. Thomas & Zeller, 2017; US EPA, 2021). Use of the National Walkability Index in both urban and rural contexts has been well-documented (Moored et al., 2024; Rockhill et al., 2025; Watson et al., 2020). The National Walkability Index (2021) consists of three built environment metrics that affect whether people walk as a mode of transportation: street intersection density, proximity to transit stops, and land use diversity (Ewing & Cervero, 2010). The mean walkability of all block groups within a tract was calculated to obtain a National Walkability Index value for each census tract in SC.

Health Metrics

Multiple health metrics for each census tract in SC were retrieved from the 2021 Population Level Analysis and Community Estimates (PLACES) data source (CDC, 2022). The PLACES program uses small area estimation and a multilevel regression and poststratification approach, integrating geocoded health surveys with detailed data from the CDC's Behavioral Risk Factor Surveillance System (BRFSS), 5-year American Community Survey estimates, and state- and county-level random effects, to estimate the geographic distribution of population disease burden and health behaviors for adults ages 18 years and older (CDC, 2023a).

Five diverse health outcomes and one key health-risk behavior were obtained for each census tract. These health metrics were chosen to represent diverse physical and mental health outcomes and behaviors that have been linked to features of the built environment, including walkability. *Depression* was the percentage of people who reported being told by a health professional they had a depressive disorder (CDC, 2024d). *Poor mental health* was the percentage of residents who reported that their mental health was not good for 14 or more days during the past 30 days (CDC, 2024c). *Poor physical health* was the percentage of respondents who reported that their physical health had not been good for 14 or more days during the past 30 days (CDC, 2024c). *Mobility disability* was the proportion who answered "yes" to "Do you have serious difficulty walking or climbing stairs?" (CDC, 2024). *Obesity* was the percentage of respondents who had a BMI ≥30.0 kg/m² calculated from self-reported weight and height (CDC, 2024). *No leisure time physical activity* was those who reported not participating in any physical activities or exercise outside their regular job (CDC, 2024b).

Social Vulnerability

Data on social vulnerability were collected for all census tracts in SC. The Social Vulnerability Index was developed by the CDC using 2021 data and comprises four sub-themes, including socioeconomic status, household composition and disability, minority status and language, and housing type and transportation, which collectively include 15 social factors. For each census tract in SC, a percentile rank was obtained for each social factor as a value between 0 and 1, with higher values indicating greater social vulnerability. Percentile ranks for each dimension were then calculated by combining the respective social factors, and an overall Social Vulnerability Index percentile was derived by calculating the average percentile ranking values for the four dimensions (CDC, 2024a).

Urbanicity

Census tracts were classified based on rurality/urbanicity using Rural Urban Community Area (RUCA) codes that are derived according to measures of population density, urbanization, and daily commuting (US Department of Agriculture, Economic Research Service [USDA ERS], 2024). RUCA primary codes ranging from 1 (most urban) to 10 (most rural) were combined into two categories of urban (codes 1-6) versus rural (codes 7-10) (DeGuzman et al., 2021; Mulrooney et al., 2023; USDA ERS, 2024).

Tract Sociodemographic Characteristics

To account for various sociodemographic characteristics, the following variables were obtained for each tract from American Community Survey 5-year estimates (2015–2019): 1) percentage of population under 125% of the federal poverty threshold; 2) percentage unemployed; 3) median household income; 4) percentage with less than high school education; 5) percentage 65 years or older; 6) percentage 17 years or younger; and 7) percentage racial/ethnic minority population.

Analysis

Descriptive statistics were used to explore walkability, social vulnerability, various health metrics and behaviors, and sociodemographic characteristics for all census tracts. To address aim one, multilevel (mixed-effects) linear regression models investigated the association between census tract walkability and health outcomes (dependent variables), while adjusting for social vulnerability and sociodemographic covariates. To account for the hierarchical structure of the data, census tracts (Level 1) were nested within counties (Level 2), and random intercepts for counties were included to account for within-county clustering of observations. For aim two (i.e., how relationships between walkability and the health metrics vary by social vulnerability), we conceptualized social vulnerability as a moderating variable given prior evidence that structural and contextual factors may influence how built environment characteristics relate to health outcomes. To accomplish this, an interaction term between centered National Walkability Index and centered Social Vulnerability Index percentile was added to the models. Continuous variables included in interaction terms (i.e., National Walkability Index and Social Vulnerability Index) were mean-centered to reduce multicollinearity (centering was applied only in moderation analyses; aims 2 and 3). The Social Vulnerability Index was scaled from 0 to 1, representing percentile ranking. Accordingly, regression coefficients can be interpreted in meaningful increments

(e.g., a 0.1 increase corresponding to a 10-percentile increase). Afterward, values for simple slopes of the interaction between centered National Walkability Index and centered Social Vulnerability Index were plotted for each health variable. Simple slopes were computed for each health metric by utilizing centered values of National Walkability Index and the overall Social Vulnerability Index percentile ranking within the study sample. Finally, to address aim 3, we again examined the relationship between walkability and health metrics moderated by social vulnerability when tracts were stratified as urban versus rural. Urbanicity was included as a stratifying variable in order to assess potential heterogeneity in these associations across fundamentally different contexts. All analyses were conducted in Stata 18 SE software (StataCorp, 2023) and tests were considered significant at $p<.05$.

Results

Table 1 shows descriptive statistics for all tracts in SC for all independent (National Walkability Index and Social Vulnerability Index) and dependent (health metrics) variables and covariates; 14 tracts were excluded due to missing data. Overall, SC had 46 counties containing between 3 and 111 census tracts (M=5, SD= 33.83) considered for this study. On average, census tract walkability scores were "below average" (M=6.89, SD=3.33, Range=1.00-18.70) (US EPA, 2021). The mean Social Vulnerability Index for all tracts in SC was moderate (M=0.49, SD=0.28, Range=0.01-0.99). Across all tracts, the mean rate of obesity (37.49%) was greatest among the examined health metrics.

Table 1. Descriptive Characteristics of Census Tracts in South Carolina (n=1089)

Tract Characteristics	N	Minimum	Maximum	Mean	Std. Deviation
Census tracts within Counties	1089	3	111	52.00	33.82
National Walkability Index	1089	1.00	18.70	6.89	3.33
Overall Social Vulnerability Index percentile, SC	1089	0.01	0.99	0.49	0.28
Depression %	1089	13.60	34.30	21.31	2.44
Poor mental health %	1089	8.50	36.40	17.79	3.21
Poor physical health %	1089	5.50	27.20	12.83	3.02
Mobility disability %	1089	2.40	36.50	15.33	5.05
Obesity %	1089	19.90	56.50	37.49	5.85
No leisure-time physical activity %	1089	11.20	53.30	26.73	7.35
Population below poverty %	1087	0.00	100.00	17.71	11.82
Population unemployed %	1088	0.00	26.80	6.96	4.38
Median household income	1089	3115	164297	27682.85	12943.82
Population with no high school diploma %	1089	0.00	47.40	13.94	8.54
Population age 65 or above %	1089	0.00	76.30	17.30	7.77
Population age 17 or below %	1089	0.00	38.20	21.36	6.09
Racial/ethnic minority population %	1089	0.00	100.00	37.64	23.43

Relationship between Walkability and Health Metrics

Table 2 represents the association between walkability and various health issues and behaviors (aim 1). The results showed that greater walkability was significantly and negatively associated with poor mental health (B=-.05, SE=.02, p=0.001), poor physical health (B=-.08, SE=.01, p<0.000), obesity (B=-.22, SE=.03, p<0.000), and no leisure time physical activity (B=-.13, SE=.03, p<0.000).

Table 2. Association Between Neighborhood Walkability and Health Metrics across Census Tracts in South Carolina (n=1089)

Variables	Depression B (SE)	Poor mental health B (SE)	Poor physical health B (SE)	Mobility disability B (SE)	Obesity B (SE)	No leisure time physical activity B (SE)
National Walkability Index	-.02 (.01)	-.05 (.02)**	-.08 (.01)***	-.04 (.03)	-.22 (.03)***	-.13 (.03)***

**$p < 0.01$
***$p < 0.001$
National Walkability Index and Social Vulnerability Index were centered to minimize multicollinearity.

Relationship between Walkability and Health Metrics Moderated by Social Vulnerability

As displayed in Table 3, results from multilevel linear regression models accounting for clustering of census tracts within counties indicated that the interaction between National Walkability Index and Social Vulnerability Index was significant and negative for poor mental health, poor physical health, obesity, and no leisure time physical activity. Random effects estimates suggested meaningful between-county variation in health outcomes, with intraclass correlation coefficients (ICC) ranging from 5.3% to 53.6% (e.g., ICC=9.6% for poor mental health; ICC=36.2% for no leisure time physical activity), and likelihood ratio tests confirmed that multilevel models provided a better fit than single-level models (p<0.001). Figures 1, 2, 3, and 4, respectively, illustrate these associations for the aforementioned variables at low, mean, and high levels of Social Vulnerability Index. Low, mean, and high levels of the Social Vulnerability Index were defined as one standard deviation below the mean, the mean, and one standard deviation above the mean, respectively, based on the distribution within the study sample. As shown in Figure 1, higher National Walkability Index was associated with lower levels of poor mental health across all levels of Social Vulnerability Index. Specifically, higher walkability was associated with greater reductions in poor mental health at low Social Vulnerability Index (B=-0.08, SE=0.02, p<0.001) and mean Social Vulnerability Index (B=-0.04, SE=0.02, p= 0.001) compared to high Social Vulnerability Index (B=-0.02, SE=0.02, p= 0.337). Similarly, at all levels of Social Vulnerability Index (low: B=-0.11, SE=0.02, p<0.001, mean: B=-0.08, SE=0.01, p<0.001, high: B=-0.06, SE=0.02, p<0.001), an increase in National Walkability Index was associated with a decrease in the prevalence of poor physical health as displayed in Figure 2. Notably, poor physical health was greatest in high socially vulnerable areas with low walkability, and it experienced the smallest decrease as the walkability score increased. This decline was greater for tracts with medium and low social vulnerability. Remarkably, obesity rate was greatest in low Social Vulnerability Index but also experienced the greatest decline (B=-0.27, SE=0.03, p<0.001) as walkability of neighborhood increased. On the other hand, high socially vulnerable areas had the lowest rate of obesity in low walkable neighborhoods and faced the smallest decrease (B=-0.17, SE=0.03, p<0.001) as walkability increased compared to low and mean Social Vulnerability Index (B=-0.22, SE=0.03, p<0.001). Lastly, as shown in Figure 4, no leisure-time physical activity declined across all levels of Social Vulnerability Index (low: B=-0.19, SE=0.03, p<0.001, mean: B=-0.13, SE=0.03, p<0.001, high: B=-0.07, SE=0.03, p=0.028).

Table 3. Association Between Neighborhood Walkability and Health Metrics Moderated by Social Vulnerability and Stratified by Urban versus Rural across Census Tracts in South Carolina (n=1089)

Variables	N	Depression B (SE)	Poor mental health B (SE)	Poor physical health B (SE)	Mobility disability B (SE)	Obesity B (SE)	No leisure time physical activity B (SE)
National Walkability Index	1089	-.02 (.01)	-.05 (.02)**	-.08 (.01)***	-.04 (.03)	-.22 (.03)***	-.13 (.03)***
Urban	888	-.03 (.02)	-.05 (.02)**	-.07 (.02)***	-.02 (.03)	-.19 (.03)***	-.10 (.03)***
Rural	201	-.07 (.05)	-.07 (.06)	-.27 (.06)***	-.42 (.11)***	-.55 (.10)***	-.50 (.11)***
Overall Social Vulnerability	1089	1.00 (.27)***	.78 (.30)**	1.08 (.28)***	1.62 (.49)**	.46 (.49)	2.80 (.52)***

Index percentile, SC							
Urban	888	1.24 (.30)***	1.11 (.34)**	1.23 (.30)***	1.67 (.55)**	.39 (.56)	3.26 (.57)***
Rural	201	.31 (.75)	-.96 (.86)	.89 (.87)	2.46 (1.52)	.84 (1.44)	1.80 (1.62)
National Walkability Index x Overall Social Vulnerability Index	1089	-.02 (.04)	.11 (.04)**	.09 (.04)*	.05 (.07)	.18 (.07)**	.20 (.01)**
Urban	888	-.05 (.04)	.07 (.05)	.06 (.04)	-.04 (.07)	.20 (.07)**	.15 (.08)
Rural	201	.22 (.18)	.17 (.21)	.36 (.21)	.81 (.37)*	.26 (.35)	.84 (.39)*
Random Effects (County Level)							
Variance (Intercepts)		0.72	0.15	0.07	0.47	4.40	2.44
Residual Variance		1.12	1.44	1.24	3.95	3.81	4.30
Intraclass Correlation Coefficients (ICC;%)		39.1%	9.6%	5.3%	10.6%	53.6%	36.2%
Model Fit Statistics							
Observation		1087	1087	1087	1087	1087	1087
Counties		46	46	46	46	46	46
Log Likelihood		-1660.47	-1765.45	-1673.42	-2313.70	-2336.20	-2387.15
Likelihood Ratio Test (vs Ordinary Least Squares)		550.76***	109.81***	26.95***	64.32***	717.64***	335.67***

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

National Walkability Index and Social Vulnerability Index were centered to minimize multicollinearity.
All models were estimated using multilevel linear regression with census tracts nested within counties (random intercepts included). Variance components and intraclass correlation coefficients are reported for county-level effects. Likelihood Ratio Tests compare multilevel models to single-level linear models.

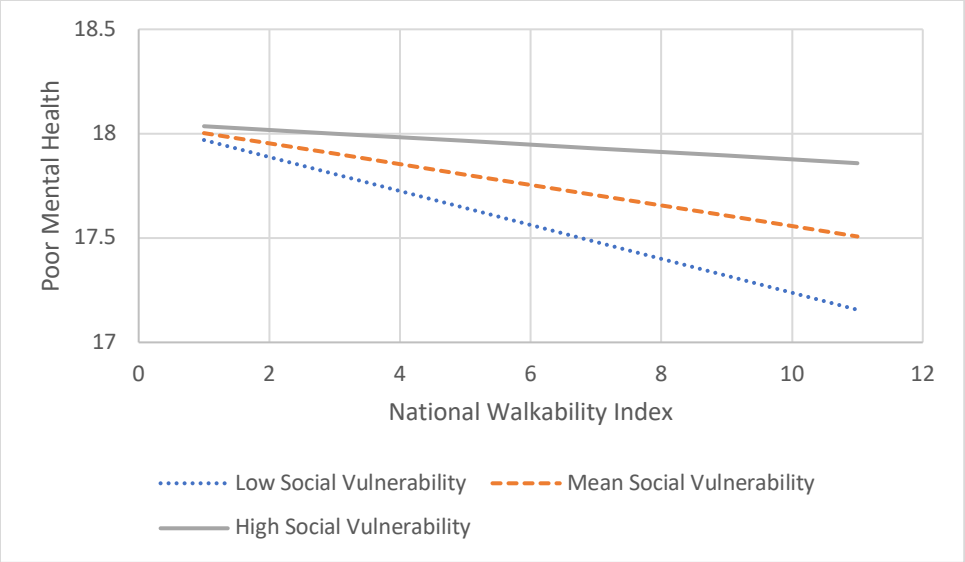

Figure 1. Relationship between National Walkability Index and Poor Mental Health by Social Vulnerability

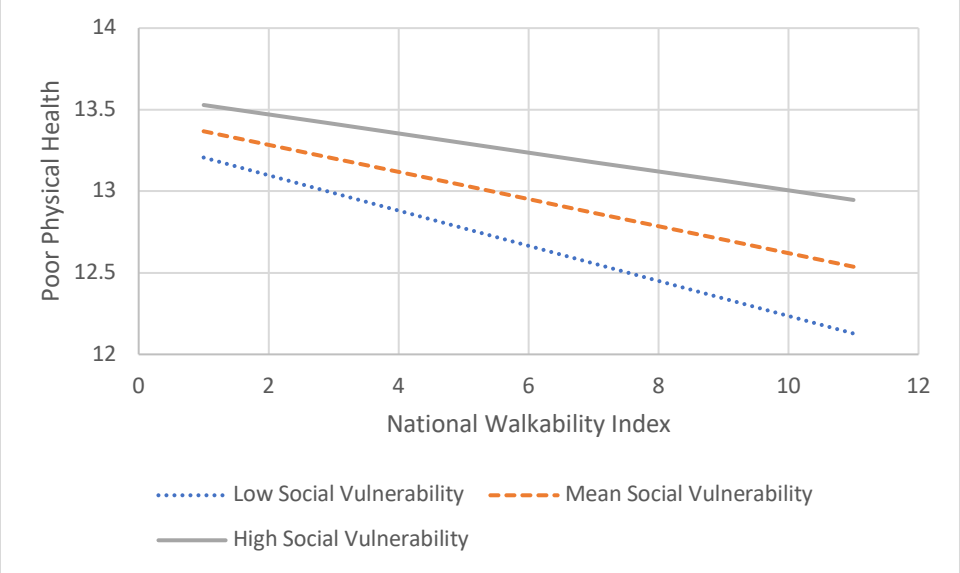

Figure 2. Relationship between National Walkability Index and Poor Physical Health by Social Vulnerability

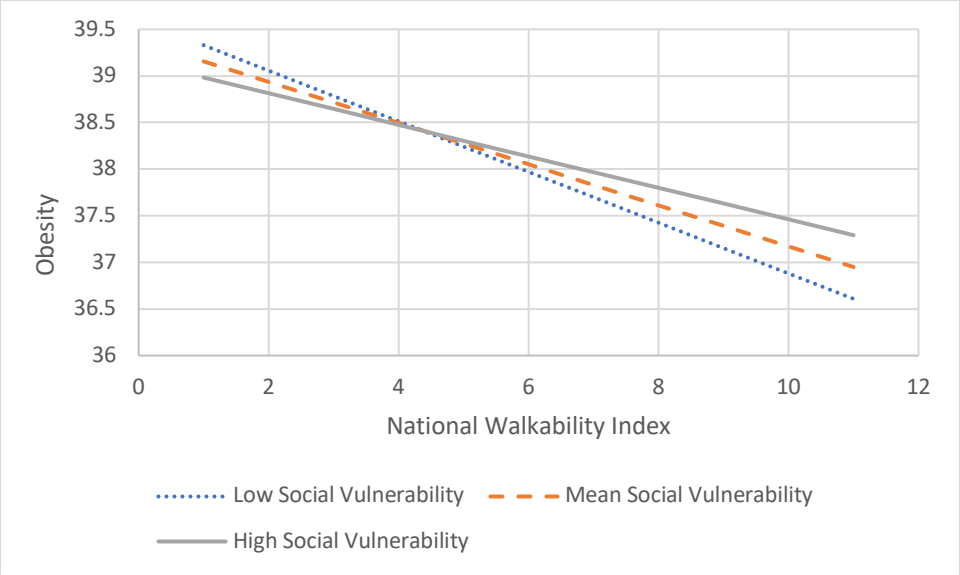

Figure 3. Relationship between National Walkability Index and Obesity by Social Vulnerability

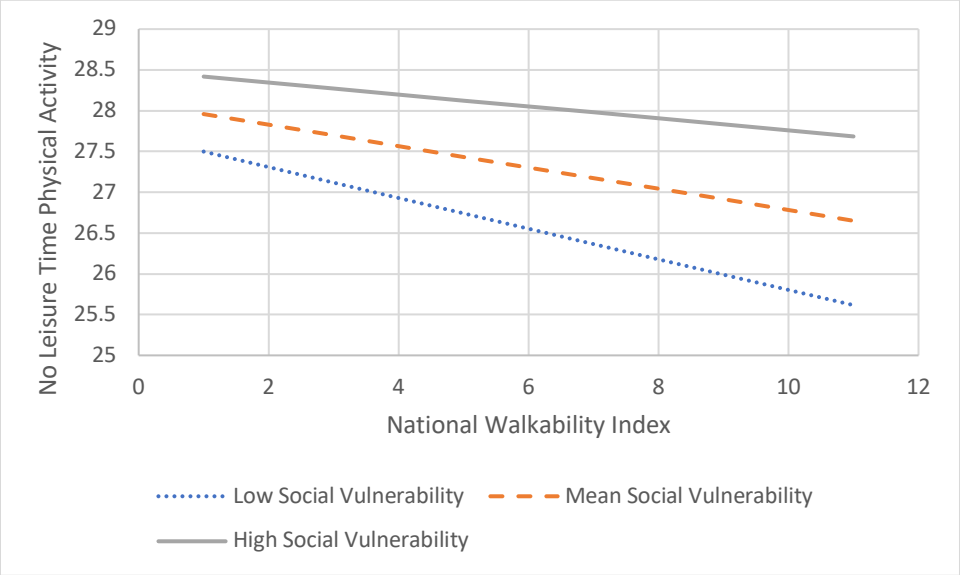

Figure 4. Relationship between National Walkability Index and No Leisure-Time Physical Activity by Social Vulnerability

Walkability and Health Metrics Relationship Moderated by Social Vulnerability Stratified by Urbanicity/Rurality

As shown in Table 3, taking into account the rural or urban classification of tracts altered the relationship between walkability and some health metrics significantly. Specifically, before including the interaction of National Walkability Index and Social Vulnerability Index, the association between walkability and poor mental health was significant only in urban tracts (B=-.05, SE=.02, $p<0.01$), while this association remained significant for poor physical health, obesity, and no leisure time physical activity. However, for mobility disability, this association became statistically significant among rural tracts (B=-.42, SE=.11, $p<0.001$). When adding the moderating effect of social vulnerability to the model, the relationships between walkability and obesity (B=.20, SE=.07, $p<0.01$) became positive and significant only in urban tracts. On the other hand, the relationship between walkability and mobility disability (B=.81, SE=.37, $p<0.05$) and walkability and no leisure-time physical activity (B=.84, SE=.39, $p<0.05$) turned positive and significant only in rural tracts.

Discussion

This study explored the relationship between neighborhood walkability and various health issues and behaviors in SC, with a focus on the moderating role of social vulnerability and the classification of urbanicity/rurality. In doing so, we demonstrate that the health benefits of walkable environments are not shared equally, especially among socially vulnerable groups. Specifically, the findings of this study provide valuable insights into the significant inverse relationship between walkability and most health issues and behaviors and how this varied at different levels of social vulnerability. In addition, the observed variation between counties, as indicated by intraclass correlations in our results, suggests that contextual, county-level factors are associated with differences in health outcomes. These results emphasize the potential of walkable neighborhoods to mitigate the prevalence of chronic diseases and risky behaviors contributing to physical and mental health, thereby promoting public health at the community level. Our findings also highlight the importance of examining such issues within an environmental justice lens and considering walkability may not be uniform and equally beneficial and available to all.

Walkability and Health Metrics

Across this sample of SC census tracts, higher levels of walkability were significantly and negatively associated with numerous health metrics, including poor mental health, poor physical health, obesity, and no leisure time physical activity. These findings are consistent with prior research, as several studies have reported an inverse association between neighborhood walkability and the prevalence of chronic diseases, depression, and cardiovascular diseases (Howell, Tu, Moineddin, Chu, et al., 2019; Keats et al., 2020; Koohsari et al., 2019). For example, one study by Yoon et al. (2017) showed that lower walkability scores in neighborhoods in California were linked to less walking behavior among individuals, ultimately leading to poor mental health. In terms of physical health status, Wang et al. (2023) found that compared to those in neighborhoods with low walkability level, participants in highly walkability neighborhoods had increased odds of sufficient physical activity and decreased odds of obesity. Similarly, many studies proved a negative association between neighborhood walkability and BMI and obesity (King et al., 2011; Smith et al., 2008; Stowe et al., 2019; Van Cauwenberg et al., 2016; Wang et al., 2023). Considering such negative associations is vital, especially in SC, where these risk factors are among the most prevalent health concerns and causes of mortality (CDC, 2023b; South Carolina Department of Public Health, 2024). Another study by de Sa and Arden (2014) demonstrated that individuals living in highly walkable areas (upper quartiles of the walkability index) are more likely to engage in leisure walking or cycling compared to those in less walkable areas. Documenting such negative associations could bring attention to the significance of walkability when redesigning the built environment to enhance population health and well-being.

Walkability and Health Metrics Moderated by Social Vulnerability

The association between walkability and the considered health metrics was moderated by social vulnerability for three health outcomes and a health risk behavior: poor mental health, poor physical health, obesity, and no leisure-time physical activity. Specifically, across all levels of social vulnerability, the rate of these health issues and behaviors decreased as walkability of neighborhoods increased. Also, except for obesity, the rate of these outcomes was greatest in high socially vulnerable areas and the lowest in low socially vulnerable areas. There may be multiple reasons for these findings. First, neighborhoods with high social vulnerability often face additional barriers, such as safety concerns, inadequate infrastructure, or fewer recreational facilities, which may limit the extent to which increased walkability translates into health benefits (Fordham et al., 2013; S. Liu et al., 2023; McKenzie et al., 2013). Second, individuals in low socially vulnerable areas may have greater access to resources, such as well-maintained sidewalks, green spaces, or community programs, that amplify the positive effects of walkability on health (Bereitschaft, 2023; Bereitschaft, 2017; Y. Liu et al., 2024). These findings suggest that while walkability is beneficial across all communities, efforts to improve neighborhood environments in highly socially vulnerable areas are critical to reducing health disparities.

On the other hand, the prevalence of obesity in neighborhoods with low walkability was more pronounced in areas with low social vulnerability but showed the greatest reduction as walkability increased. In contrast, while individuals in high social vulnerability areas had the lowest obesity rates in low-walkability neighborhoods, they experienced the smallest reduction in obesity as walkability improved. Several factors could help explain these observed patterns. For example, in low social vulnerability areas with low walkability, residents might rely more on car transportation and sedentary behaviors due to the design

of their neighborhoods (Chakrabarti & Shin, 2017). These behaviors could contribute to higher obesity rates despite their lower social vulnerability. In terms of the sharpest decline in the rate of obesity in areas with low social vulnerability as walkability increases, residents may be better positioned to take advantage of improvements in high walkable areas due to access to complementary resources (e.g., better-maintained sidewalks, recreational facilities, and safer environments) (Høyer-Kruse et al., 2024). Also, cultural or lifestyle differences across neighborhoods could play a role, where residents in low social vulnerability areas may already be more inclined to adopt physical activity behaviors that align with increased walkability compared to those in high social vulnerability areas.

Walkability and Health Metrics Moderated by Social Vulnerability and Stratified by Urbanicity/Rurality

While several prior studies have examined the relationship between walkability and multiple health metrics mentioned above, only a few have considered interaction effects between National Walkability Index and Social Vulnerability Index or based on urbanicity or rurality (Baobeid et al., 2021; Kowaleski-Jones et al., 2018; Lovasi et al., 2011; Rohrer et al., 2004; Van Cauwenberg et al., 2016; Wang et al., 2023; Howell, Tu, Moineddin, Chen, et al., 2019; Wali, 2023). According to our findings, the relationship between walkability and health varied depending on the interaction between National Walkability Index and Social Vulnerability Index and whether the tracts were in rural or urban areas. Specifically, the association between walkability and several health metrics (i.e., poor physical health, obesity, and no leisure time physical activity) was significant and negative in both urban and rural tracts. However, these associations became positive in both rural and urban areas after considering the moderation effect of social vulnerability. Such unexpected observations might be due to the complex interplay between social vulnerability and access to resources in both urban and rural areas. For instance, in socially vulnerable neighborhoods, even in walkable environments, barriers such as economic hardship, limited access to healthcare, healthy food options, safety concerns, or poorly maintained infrastructure may reduce the potential benefits of walkability, independent of urbanicity/rurality (Bereitschaft, 2023).

Recognizing how the association between walkability and health outcomes differs in rural versus urban areas, including variations by social vulnerability, is critical to understanding and promoting physical and mental health statuses in these diverse settings. Particularly, in urban areas, where infrastructure and destinations are typically more concentrated, increased walkability often leads to greater opportunities for better overall health and improved access to resources (Westenhöfer et al., 2023). However, in socially vulnerable urban neighborhoods, these benefits are frequently limited by factors such as safety concerns and economic barriers (Bereitschaft, 2023). In contrast, in rural settings with high social vulnerability, there might be fewer organized and sustained community programs promoting health and wellness, leading to isolation, loneliness, and reduced participation in social or physical activities, causing several health-concerning consequences, such as an increased rate of mobility disability and no leisure time physical activity (Shediac-Rizkallah & Bone, 1998; Williams et al., 2022). One study by Thielman et al. (2015) showed that in small towns, the rate of no leisure time physical activity was lower in areas with higher walkability. These risk factors may be multiplied by a lack of strategies targeting enhancing connectivity, addressing transportation gaps, and tailoring walkable infrastructure to better serve dispersed populations. Also, the fear of being unsafe and insecure in high vulnerability-urban areas could prevent people from engaging in physical activities even with greater walkability in their neighborhoods (Chupak et al., 2025).

Implications for Research and Practice

This study lends itself to a wealth of ideas for future research and practice. To begin, taking into account the complex relationship between walkability and health metrics moderated by social vulnerability and stratified by urbanicity/rurality, future studies could potentially focus on each of these directions further to obtain more nuanced findings (e.g., examining specific neighborhood design elements, individual versus community health behavior/outcomes, particular social determinants of health). In addition, other neighborhood factors contributing to health beyond walkability, such as aesthetics and safety, are additional environmental factors that merit examination. Also, the present methodology could be replicated in different states and regions with diverse levels of walkability, health, vulnerability, and urbanicity, and the results compared with each other. Researchers should also explore the preliminary relationships identified here in more detail, such as better understanding the thresholds or augmentations in walkability necessary to impact or achieve various health objectives (e.g., a 5% reduction in no leisure time physical activity). Finally, future analyses could also parse out which components of the Social Vulnerability Index most strongly moderate the effects of walkability on health, or develop a vulnerability-adjusted walkability framework that delineates Social Vulnerability Index thresholds at which the benefits of walkability are attenuated.

Regarding implications for policymakers and public health professionals, our findings provide preliminary support for embracing greater walkability to be associated with better mental and physical health (Zhu et al., 2013). As such improvements are made in communities, more natural intervention research is needed to ascertain and more rigorously document the longitudinal impacts of enhanced walkability (Acciai et al., 2023; Goon et al., 2020; White et al., 2021). In addition, problems specific to urban (e.g., traffic, crowded spaces) and rural (e.g., lack of resources) contexts require implementing community-based interventions to target health issues effectively and efficiently. Another critical finding beneficial for decision-makers is to consider the moderation effect of social vulnerability on the relationship between walkability and different health metrics. For example, efforts to increase walkability may need to be combined with (or follow)

policies and programs that ameliorate social vulnerability barriers which may be impeding the potential association of a walkable neighborhood with improved health. Overall, as more is learned about how walkability is associated with health in diverse contexts, more robust evidence (e.g., additional studies, longitudinal study designs) will be valuable to reinforce the preliminary findings reported here. In the meantime, studies such as the present one provide a replicable, cost-effective means of surveillance and predictive modeling for better understanding and forecasting the impacts of improved walkability on health. By integrating accessible environmental and public health datasets from the EPA, CDC, and other organizations, states and communities can develop risk stratification profiles (e.g., for cities, neighborhoods, council/planning districts) and prioritize where walkability interventions may be most fruitful.

Strengths and Limitations

This study had a number of limitations. First, its cross-sectional design limits the ability to infer causality, and it is possible that healthy people may opt to live in more walkable environments (an issue of self-selection). Second, this research used the National Walkability Index, an index developed initially to assess individual-level physical activity, as a measure to investigate broader health outcomes on an ecological scale. While walkability indices provide valuable insights into neighborhood-level characteristics that influence physical activity, they may not directly capture the built environment and other social determinants of health. The National Walkability Index, including its current components, street intersection density, proximity to transit stops, and land use diversity, may also be less relevant in rural areas. Indeed, traditional walkability measurements are often inadequate for individuals living outside urban areas, as these metrics typically do not consider walking that is not directed toward a specific amenity. Future research needs to develop tools and metrics that can reliably measure walkability in rural communities and provide easily accessible results based on physical addresses. These tools should incorporate assessments of sidewalks, safe street crossings, town centers, trails, parks, other green spaces, and rural-specific destinations, like relaxing places and additional safety considerations (Maddock et al., 2024). Third, although this study integrated diverse secondary data from multiple reliable sources, including primary data about walkability and/or health may yield additional insights. In addition, other relevant variables, such as neighborhood greenery and aesthetics of the built environment, were not considered. Fourth, our approach is subject to the modifiable areal unit problem, where the results may vary depending on how the geographic boundaries of analysis are defined, influencing the observed relationships between walkability and health outcomes (Diez Roux, 2001, 2008). Census tracts in SC differ in size, demographic makeup, and socioeconomic status, can change borders gradually, and may span multiple neighborhoods. Therefore, it is possible to grasp only a fraction of this diversity and complexity when assessing walkability and health metrics at the census tract level. Finally, since this study uses aggregate data at the census tract level, the findings may be affected by ecological fallacy, in that patterns observed in neighborhoods might not apply to individuals, which could limit the generalizability of the results.

On the other hand, this study has several strengths worth mentioning. First and foremost, we considered the relationship between walkability and several health metrics relevant to mental and physical health simultaneously. Second, to our knowledge, no study to date has considered such relationships in the context of an interaction between National Walkability Index and Social Vulnerability Index. Third, including RUCA classifications (i.e., stratifying by urban and rural areas) and focusing on a state with diverse and egregious geographic and sociodemographic health disparities provided insightful results regarding the association between walkability and health metrics in varied contexts.

Conclusion

In conclusion, our findings showed that higher walkability was associated with lower prevalence of several health outcomes and risk behaviors. In addition, greater walkability in low and medium socially vulnerable areas was negatively associated with multiple health outcomes, while higher walkability was not associated with some health outcomes in high socially vulnerable areas. However, these relationships varied when considering urbanicity/rurality. The insights gained from this study can be used to develop relevant interventions and policies to consider walkability (e.g., improving infrastructure such as sidewalks, green spaces, and access to essential services) alongside social vulnerability (e.g., addressing systemic barriers like economic inequality), based on the specific contexts and associated issues to promote population health and well-being.

Correspondence should be addressed to

Andrew T. Kaczynski

Department of Health Promotion, Education, and Behavior

Arnold School of Public Health, University of South Carolina

915 Greene Street, Room 539

Columbia, SC, 29208

atkaczyn@mailbox.sc.edu

(803) 777-7063

- Farnaz Hesam Shariati: 0000-0002-2892-4104
- Anna L. Chupak: 0000-0002-8917-2145
- Erin Looney: 0000-0002-2218-7676
- Shirelle H. Hallum: 0009-0008-1805-2665
- Mojtaba Kazemian: 0009-0000-5458-2382

Acknowledgements

Not applicable

Ethics Approval and Consent to Participate

Not applicable. We used datasets that are publicly available.

https://data.cdc.gov/500-Cities-Places/PLACES-Local-Data-for-Better-Health-County-Data-20/swc5-untb/explore

https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/

https://www.epa.gov/smartgrowth/national-walkability-index-user-guide-and-methodology

https://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes/documentation/

Consent for Publication

Not applicable

Conflict of Interest Statement

The authors declare that they have no competing interests.

Authors' Contributions

F.HS. was in charge of formal analysis, investigation, data curation, writing and original draft preparation, and visualization. A.L.C. was in charge of formal analysis, data curation, writing, and reviewing. S.H.H. was in charge of data curation. E.L., C.M.M., and M.K. were in charge of writing and reviewing extensively. A.T.K. was in charge of project administration, methodology, data curation, writing original draft preparation, writing and reviewing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding

This study was supported by the University of South Carolina, Office of Research.

List of Abbreviations

BMI: Body Mass Index
BRFSS: Behavioral Risk Factor Surveillance System
CDC: Centers for Disease Control and Prevention
EPA: Environmental Protection Agency
PLACES: Population Level Analysis and Community Estimates
RUCA: Rural Urban Community Area
SC: South Carolina
US: United States

References

Acciai, F., DeWeese, R. S., Lloyd, K., Yedidia, M. J., Kennedy, M., DiSantis, K. I., Tulloch, D., & Ohri-Vachaspati, P. (2023). The relationship between changes in neighborhood physical environment and changes in physical activity among children: A prospective cohort study. *International Journal of Behavioral Nutrition and Physical Activity*, *20*(1), 82. https://doi.org/10.1186/s12966-023-01478-2

Adams, M. C. B., Hudson, C. L., Perkins, M. L., Hurley, R. W., & Topaloglu, U. (2025). Leveraging the Rural-Urban Commuting Area Tool to Address Geographic Disparities in Cancer Care: A Dual-Application Framework for Institutional and National Initiatives. *JCO Clinical Cancer Informatics*, (9), e2500122. https://doi.org/10.1200/CCI-25-00122

America's Health Rankings. (2021). America's Health Rankings. https://www.americashealthrankings.org/publications/reports/2021-disparities-report/state-summaries-south-carolina

An, R., & Xiang, X. (2015). Social vulnerability and leisure-time physical inactivity among US adults. *American Journal of Health Behavior*, *39*(6), 751–760.

Anderson, E., & Durstine, J. L. (2019). Physical activity, exercise, and chronic diseases: A brief review. *Sports Medicine and Health Science*, *1*(1), 3–10.

Andrew, M. K. (2015). Frailty and social vulnerability. *Frailty in Aging*, *41*, 186–195.

Asiamah, N., Vieira, E. R., Gasana, J., Conduah, A. K., & Eduafo, R. (2023). The moderating influences of social networks on the relationship between neighbourhood walkability and sedentary behaviour in community-dwelling older adults in Accra, Ghana. *Journal of Public Health*, *31*(5), 789–798.

Baobeid, A., Koç, M., & Al-Ghamdi, S. G. (2021). Walkability and its relationships with health, sustainability, and livability: Elements of physical environment and evaluation frameworks. *Frontiers in Built Environment*, *7*, 721218.

Bereitschaft, B. (2017). Equity in neighbourhood walkability? A comparative analysis of three large US cities. *Local Environment*, *22*(7), 859–879.

Bereitschaft, B. (2023). Do socially vulnerable urban populations have access to walkable, transit-accessible neighborhoods? A nationwide analysis of large US metropolitan areas. *Urban Science*, *7*(1), 6.

Bernhart, J. A., Wende, M. E., Kaczynski, A. T., Wilcox, S., Dunn, C. G., & Hutto, B. (2022). Assessing the walkability environments of churches in a rural southeastern county of the United States. *Journal of Public Health Management and Practice*, *28*(1), E170–E177.

Booth, F. W., Roberts, C. K., Thyfault, J. P., Ruegsegger, G. N., & Toedebusch, R. G. (2017). Role of Inactivity in Chronic Diseases: Evolutionary Insight and Pathophysiological Mechanisms. *Physiological Reviews*, *97*(4), 1351–1402. https://doi.org/10.1152/physrev.00019.2016

Brown, A. F., Ma, G. X., Miranda, J., Eng, E., Castille, D., Brockie, T., Jones, P., Airhihenbuwa, C. O., Farhat, T., Zhu, L., & Trinh-Shevrin, C. (2019). Structural Interventions to Reduce and Eliminate Health Disparities. *American Journal of Public Health*, *109*(S1), S72–S78. https://doi.org/10.2105/AJPH.2018.304844

Bucko, A. G., Porter, D. E., Saunders, R., Shirley, L., Dowda, M., & Pate, R. R. (2021). Walkability indices and children's walking behavior in rural vs. Urban areas. *Health & Place*, *72*, 102707. https://doi.org/10.1016/j.healthplace.2021.102707

CDC. (2022). Data.CDC.Gov. https://data.cdc.gov/500-Cities-Places/PLACES-Local-Data-for-Better-Health-County-Data-20/swc5-untb/explore

CDC. (2023a, July 18). *PLACES Methodology*. Centers for Disease Control and Prevention. https://www.cdc.gov/places/methodology/index.html

CDC. (2023b, September 13). *South Carolina*. https://www.cdc.gov/nchs/pressroom/states/southcarolina/sc.htm

CDC. (2024a). *CDC/ATSDR/Social Vulnerability Index*. https://hazards.fema.gov/nri/social-vulnerability

CDC. (2024b). *Health Risk Behaviors*. PLACES: Local Data for Better Health. https://www.cdc.gov/places/measure-definitions/health-risk-behaviors.html

CDC. (2024c). *Health Status*. PLACES: Local Data for Better Health. https://www.cdc.gov/places/measure-definitions/health-status.html

CDC. (2024d). *Methodology*. PLACES: Local Data for Better Health. https://www.cdc.gov/places/methodology/index.html

CDC. (2024e, November 6). *Adult Physical Inactivity Outside of Work*. Physical Activity. https://www.cdc.gov/physical-activity/php/data/inactivity-maps.html

Centers for Disease Control and Prevention [CDC]. (2024). *Health Outcomes*. PLACES: Local Data for Better Health. https://www.cdc.gov/places/measure-definitions/health-outcomes.html

Chakrabarti, S., & Shin, E. J. (2017). Automobile dependence and physical inactivity: Insights from the California Household Travel Survey. *Journal of Transport & Health*, *6*, 262–271.

Chupak, A. L., Hallum, S. H., Shariati, F. H., Looney, E., & Kaczynski, A. T. (2025). Identifying disparities in the relationship between neighborhood walkability and active transportation safety within South Carolina. *Journal of Transport & Health*, *41*, 101960.

Clarke, P., & Gallagher, N. A. (2013). Optimizing Mobility in Later Life: The Role of the Urban Built Environment for Older Adults Aging in Place. *Journal of Urban Health*, *90*(6), 997–1009. https://doi.org/10.1007/s11524-013-9800-4

de Sa, E., & Ardern, C. I. (2014). Neighbourhood walkability, leisure-time and transport-related physical activity in a mixed urban–rural area. *PeerJ*, *2*, e440.

DeGuzman, P. B., Huang, G., Lyons, G., Snitzer, J., & Keim-Malpass, J. (2021). Rural Disparities in Early Childhood Well Child Visit Attendance. *Journal of Pediatric Nursing*, *58*, 76–81. https://doi.org/10.1016/j.pedn.2020.12.005

Diez Roux, A. V. (2001). Investigating neighborhood and area effects on health. *American Journal of Public Health*, *91*(11), 1783–1789.

Diez Roux, A. V. (2008). Next steps in understanding the multilevel determinants of health. *Journal of Epidemiology and Community Health*, *62*(11), 957–959. https://doi.org/10.1136/jech.2007.064311

Diez-Roux, A. V. (2003). Residential Environments and Cardiovascular Risk. *Journal of Urban Health: Bulletin of the New York Academy of Medicine*, *80*(4), 569–589. https://doi.org/10.1093/jurban/jtg065

Diez-Roux, A. V. (2007). Neighborhoods and health: Where are we and were do we go from here? *Revue d'epidemiologie et de Sante Publique*, *55*(1), 13–21.

Diez-Roux, A. V. (2016). Neighborhoods and health: What do we know? What should we do? *American Journal of Public Health*, *106*(3), 430.

Diez-Roux, A. V., & Mair, C. (2010). Neighborhoods and health. *Annals of the New York Academy of Sciences*, *1186*(1), 125–145. https://doi.org/10.1111/j.1749-6632.2009.05333.x

Diez-Roux, A. V., Schwartz, S., & Susser, E. (2017). Ecological variables, ecological studies, and multilevel studies in public health research. *Oxford Textbook of Global Public Health*, *411*, 493–507.

Edwards, N., & Dulai, J. (2018). Examining the relationships between walkability and physical activity among older persons: What about stairs? *BMC Public Health*, *18*, 1–11.

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association*, *76*(3), 265–294.

Fan, J. X., Wen, M., & Wan, N. (2017). Built environment and active commuting: Rural-urban differences in the U.S. *SSM - Population Health*, *3*, 435–441. https://doi.org/10.1016/j.ssmph.2017.05.007

Fordham, M., Lovekamp, W. E., Thomas, D. S., & Phillips, B. D. (2013). Understanding social vulnerability. *Social Vulnerability to Disasters*, *2*, 1–29.

Foster, S., & Giles-Corti, B. (2008). The built environment, neighborhood crime and constrained physical activity: An exploration of inconsistent findings. *Preventive Medicine*, *47*(3), 241–251.

Goon, S., Kontulainen, S., & Muhajarine, N. (2020). Neighborhood built environment measures and association with physical activity and sedentary time in 9–14-year-old children in Saskatoon, Canada. *International Journal of Environmental Research and Public Health*, *17*(11), 3837.

Gordon-Larsen, P., Nelson, M. C., Page, P., & Popkin, B. M. (2006). Inequality in the built environment underlies key health disparities in physical activity and obesity. *Pediatrics*, *117*(2), 417–424.

Hansmann, K. J., Grabow, M., & McAndrews, C. (2022). Health equity and active transportation: A scoping review of active transportation interventions and their impacts on health equity. *Journal of Transport & Health*, *25*, 101346.

Harris, M. A. (2018). The relationship between physical inactivity and mental wellbeing: Findings from a gamification-based community-wide physical activity intervention. *Health Psychology Open*, *5*(1), 2055102917753853. https://doi.org/10.1177/2055102917753853

Howell, N. A., Tu, J. V., Moineddin, R., Chen, H., Chu, A., Hystad, P., & Booth, G. L. (2019). Interaction between neighborhood walkability and traffic-related air pollution on hypertension and diabetes: The CANHEART cohort. *Environment International*, *132*, 104799.

Howell, N. A., Tu, J. V., Moineddin, R., Chu, A., & Booth, G. L. (2019). Association Between Neighborhood Walkability and Predicted 10-Year Cardiovascular Disease Risk: The CANHEART (Cardiovascular Health in Ambulatory Care Research Team) Cohort. *Journal of the American Heart Association*, *8*(21), e013146. https://doi.org/10.1161/JAHA.119.013146

Høyer-Kruse, J., Schmidt, E. B., Hansen, A. F., & Pedersen, M. R. L. (2024). The interplay between social environment and opportunities for physical activity within the built environment: A scoping review. *BMC Public Health*, *24*(1), 2361. https://doi.org/10.1186/s12889-024-19733-x

Kaczynski, A. T. (2010). Neighborhood walkability perceptions: Associations with amount of neighborhood-based physical activity by intensity and purpose. *Journal of Physical Activity and Health*, *7*(1), 3–10.

Kaczynski, A. T., Robertson-Wilson, J., & Decloe, M. (2012). Interaction of perceived neighborhood walkability and self-efficacy on physical activity. *Journal of Physical Activity and Health*, *9*(2), 208–217.

Kasehagen, L., Busacker, A., Kane, D., & Rohan, A. (2012). Associations Between Neighborhood Characteristics and Physical Activity Among Youth Within Rural–Urban Commuting Areas in the US. *Maternal and Child Health Journal*, *16*(S2), 258–267. https://doi.org/10.1007/s10995-012-1188-3

Keats, M. R., Cui, Y., DeClercq, V., Grandy, S. A., Sweeney, E., & Dummer, T. J. (2020). Associations between neighborhood walkability, physical activity, and chronic disease in Nova Scotian adults: An Atlantic PATH cohort study. *International Journal of Environmental Research and Public Health*, *17*(22), 8643.

King, A. C., Sallis, J. F., Frank, L. D., Saelens, B. E., Cain, K., Conway, T. L., Chapman, J. E., Ahn, D. K., & Kerr, J. (2011). Aging in neighborhoods differing in walkability and income: Associations with physical activity and obesity in older adults. *Social Science & Medicine*, *73*(10), 1525–1533. https://doi.org/10.1016/j.socscimed.2011.08.032

Kocjan, G. Z., Avsec, A., & Kavčič, T. (2024). Feeling too low to be active: Physical inactivity mediates the relationship between mental and physical health. *Social Science & Medicine*, *341*, 116546.

Koohsari, M. J., McCormack, G. R., Nakaya, T., Shibata, A., Ishii, K., Yasunaga, A., Hanibuchi, T., & Oka, K. (2019). Urban design and Japanese older adults' depressive symptoms. *Cities*, *87*, 166–173.

Kowaleski-Jones, L., Zick, C., Smith, K. R., Brown, B., Hanson, H., & Fan, J. (2018). Walkable neighborhoods and obesity: Evaluating effects with a propensity score approach. *SSM-Population Health*, *6*, 9–15.

Kumar, S., & Preetha, G. S. (2012). Health promotion: An effective tool for global health. *Indian Journal of Community Medicine: Official Publication of Indian Association of Preventive & Social Medicine*, *37*(1), 5.

Kurth, T., Gaziano, J. M., Berger, K., Kase, C. S., Rexrode, K. M., Cook, N. R., Buring, J. E., & Manson, J. E. (2002). Body mass index and the risk of stroke in men. *Archives of Internal Medicine*, *162*(22), 2557–2562.

Laddu, D., Paluch, A. E., & LaMonte, M. J. (2021). The role of the built environment in promoting movement and physical activity across the lifespan: Implications for public health. *Progress in Cardiovascular Diseases*, *64*, 33–40.

Lauwers, L., Leone, M., Guyot, M., Pelgrims, I., Remmen, R., Van den Broeck, K., Keune, H., & Bastiaens, H. (2021). Exploring how the urban neighborhood environment influences mental well-being using walking interviews. *Health & Place*, *67*, 102497.

Lavie, C. J., Ozemek, C., Carbone, S., Katzmarzyk, P. T., & Blair, S. N. (2019). Sedentary Behavior, Exercise, and Cardiovascular Health. *Circulation Research*, *124*(5), 799–815. https://doi.org/10.1161/CIRCRESAHA.118.312669

Leslie, E., Coffee, N., Frank, L., Owen, N., Bauman, A., & Hugo, G. (2007). Walkability of local communities: Using geographic information systems to objectively assess relevant environmental attributes. *Health & Place*, *13*(1), 111–122.

Leyden, K. M. (2003). Social capital and the built environment: The importance of walkable neighborhoods. *American Journal of Public Health*, *93*(9), 1546–1551.

Link, B. G., & Phelan, J. (1995). Social conditions as fundamental causes of disease. *Journal of Health and Social Behavior*, 80–94.

Liu, S., Morin, S. B., Bourand, N. M., DeClue, I. L., Delgado, G. E., Fan, J., Foster, S. K., Imam, M. S., Johnston, C. B., & Joseph, F. B. (2023). Social vulnerability and risk of suicide in US adults, 2016-2020. *JAMA Network Open*, *6*(4), e239995–e239995.

Liu, Y., Gu, X., Wang, Z., & Anderson, A. (2024). Urban greenery distribution and its link to social vulnerability. *Urban Forestry & Urban Greening*, *101*, 128542.

Lovasi, G. S., Grady, S., & Rundle, A. (2011). Steps forward: Review and recommendations for research on walkability, physical activity and cardiovascular health. *Public Health Reviews*, *33*(2), 484–506.

Macintyre, S., Ellaway, A., & Cummins, S. (2002). Place effects on health: How can we conceptualise, operationalise and measure them? *Social Science & Medicine*, *55*(1), 125–139.

Maddock, J. E., Perry, C., Seguin-Fowler, R., Diekman, N. F., Currier, J., Winkle, J., Lenstra, N., & Franklin, H. (2024). Is Walk Score a useful tool for measuring walkability in rural communities? *The Journal of Rural Health: Official Journal of the American Rural Health Association and the National Rural Health Care Association*, *41*(2), e12895.

Mah, J., Rockwood, K., Stevens, S., Keefe, J., & Andrew, M. K. (2023). Do interventions reducing social vulnerability improve health in community dwelling older adults? A systematic review. *Clinical Interventions in Aging*, 447–465.

Makram, O. M., Pan, A., Parekh, T., Maddock, J. E., & Kash, B. (2025). Exploring the relationship between neighborhood walkability and mental health: A study of urban areas in Texas. *Heliyon*, *11*(4). https://www.cell.com/heliyon/fulltext/S2405-8440(25)01091-6?uuid=uuid%3A6fba79c2-9452-41ab-b800-a2447c5dd117

Mazumdar, S., Learnihan, V., Cochrane, T., & Davey, R. (2018). The built environment and social capital: A systematic review. *Environment and Behavior*, *50*(2), 119–158.

McCormack, G. R., Spence, J. C., McHugh, T.-L., & Mummery, W. K. (2022). The effect of neighborhood walkability on changes in physical activity and sedentary behavior during a 12-week pedometer-facilitated intervention. *PLOS ONE*, *17*(12), e0278596. https://doi.org/10.1371/journal.pone.0278596

McKenzie, T. L., Moody, J. S., Carlson, J. A., Lopez, N. V., & Elder, J. P. (2013). Neighborhood income matters: Disparities in community recreation facilities, amenities, and programs. *Journal of Park and Recreation Administration*, *31*(4), 12.

Moored, K. D., Crane, B. M., Carlson, M. C., Dunlap, P. M., Brach, J. S., & Rosso, A. L. (2024). Neighborhood walkability is associated with global positioning system-derived community mobility of older adults. *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences*, *79*(7), glae132.

Mulrooney, T., Liang, C.-L., Kurkalova, L. A., McGinn, C., & Okoli, C. (2023). Quantitatively defining and mapping rural: A case study of North Carolina. *Journal of Rural Studies*, *97*, 47–56. https://doi.org/10.1016/j.jrurstud.2022.11.011

National Heart, Lung, and Blood Institute. (2022). Overweight and Obesity-NIH. https://www.nhlbi.nih.gov/health/overweight-and-obesity/causes

National Institute of Mental Health. (2021). *Major Depression—National Institute of Mental Health (NIMH)*. https://www.nimh.nih.gov/health/statistics/major-depression

Ohrnberger, J., Fichera, E., & Sutton, M. (2017). The relationship between physical and mental health: A mediation analysis. *Social Science & Medicine*, *195*, 42–49.

Pan, A., Sun, Q., Okereke, O. I., Rexrode, K. M., & Hu, F. B. (2011). Depression and risk of stroke morbidity and mortality: A meta-analysis and systematic review. *Jama*, *306*(11), 1241–1249.

Penninx, B. W., Beekman, A. T., Honig, A., Deeg, D. J., Schoevers, R. A., Van Eijk, J. T., & Van Tilburg, W. (2001). Depression and cardiac mortality: Results from a community-based longitudinal study. *Archives of General Psychiatry*, *58*(3), 221–227.

Pereira, M. F., Vale, D. S., & Santana, P. (2023). Is walkability equitably distributed across socio-economic groups?–A spatial analysis for Lisbon metropolitan area. *Journal of Transport Geography*, *106*, 103491.

Powell-Wiley, T. M., Poirier, P., Burke, L. E., Després, J.-P., Gordon-Larsen, P., Lavie, C. J., Lear, S. A., Ndumele, C. E., Neeland, I. J., Sanders, P., St-Onge, M.-P., & On behalf of the American Heart Association Council on Lifestyle and Cardiometabolic Health; Council on Cardiovascular and Stroke Nursing; Council on Clinical Cardiology; Council on Epidemiology and Prevention; and Stroke Council. (2021). Obesity and Cardiovascular Disease: A Scientific Statement From the American Heart Association. *Circulation*, *143*(21). https://doi.org/10.1161/CIR.0000000000000973

Rees-Punia, E., Hathaway, E. D., & Gay, J. L. (2018). Crime, perceived safety, and physical activity: A meta-analysis. *Preventive Medicine*, *111*, 307–313.

Reis, R. S., Hino, A. A. F., Rech, C. R., Kerr, J., & Hallal, P. C. (2013). Walkability and physical activity: Findings from Curitiba, Brazil. *American Journal of Preventive Medicine*, *45*(3), 269–275.

Riggs, W. (2016). Inclusively walkable: Exploring the equity of walkable housing in the San Francisco Bay Area. *Local Environment*, *21*(5), 527–554.

Riggs, W., & Sethi, S. A. (2020). Multimodal travel behaviour, walkability indices, and social mobility: How neighbourhood walkability, income and household characteristics guide walking, biking & transit decisions. *Local Environment*, *25*(1), 57–68.

Rockhill, S. M., Soto, G. W., Whitfield, G. P., Barry, V., & Fletcher, K. (2025). Associations between National walkability Index and Traffic-Related pedestrian Deaths, United States, 2017–2019. *Transportation Research Interdisciplinary Perspectives*, *31*, 101404. https://doi.org/10.1016/j.trip.2025.101404

Rohrer, J., Pierce, J., & Denison, A. (2004). Walkability and self-rated health in primary care patients. *BMC Family Practice*, *5*(1), 29. https://doi.org/10.1186/1471-2296-5-29

Sallis, J. F., Floyd, M. F., Rodríguez, D. A., & Saelens, B. E. (2012). Role of built environments in physical activity, obesity, and cardiovascular disease. *Circulation*, *125*(5), 729–737.

Salvo, G., Lashewicz, B. M., Doyle-Baker, P. K., & McCormack, G. R. (2018). Neighbourhood built environment influences on physical activity among adults: A systematized review of qualitative evidence. *International Journal of Environmental Research and Public Health*, *15*(5), 897.

Shediac-Rizkallah, M. C., & Bone, L. R. (1998). Planning for the sustainability of community-based health programs: Conceptual frameworks and future directions for research, practice and policy. *Health Education Research*, *13*(1), 87–108.

Sher, Y., Lolak, S., & Maldonado, J. R. (2010). The Impact of Depression in Heart Disease. *Current Psychiatry Reports*, *12*(3), 255–264. https://doi.org/10.1007/s11920-010-0116-8

Smith, K. R., Brown, B. B., Yamada, I., Kowaleski-Jones, L., Zick, C. D., & Fan, J. X. (2008). Walkability and body mass index: Density, design, and new diversity measures. *American Journal of Preventive Medicine*, *35*(3), 237–244.

Sonawane, K., Borse, K. N., Jefferson, M., Damgacioglu, H., Carpenter, M. J., Pearce, J. L., Ogretmen, B., Paczesny, S., O'Bryan, J. P., Obeid, J. S., Ford, M. E., & Deshmukh, A. A. (2024). Developing catchment area data dashboards for cancer centers: A stakeholder-engaged approach. *Preventive Oncology & Epidemiology*, *2*(1), 2394193. https://doi.org/10.1080/28322134.2024.2394193

South Carolina Department of Public Health. (2024). *South Carolina Department of Public Health*. https://dph.sc.gov/professionals/public-health-data/behavioral-risk-factor-surveillance-system-brfss

StataCorp. (2023). *Stata Statistical Software: Release 18. College Station, TX: StataCorp LLC.* [Computer software]. https://www.stata.com/support/faqs/resources/citing-software-documentation-faqs/

Stowe, E. W., Hughey, S. M., Hallum, S. H., & Kaczynski, A. T. (2019). Associations between walkability and youth obesity: Differences by urbanicity. *Childhood Obesity*, *15*(8), 555–559.

Tao, Y., Ma, J., Shen, Y., & Chai, Y. (2022). Neighborhood effects on health: A multilevel analysis of neighborhood environment, physical activity and public health in suburban Shanghai. *Cities*, *129*, 103847.

Thielman, J., Rosella, L., Copes, R., Lebenbaum, M., & Manson, H. (2015). Neighborhood walkability: Differential associations with self-reported transport walking and leisure-time physical activity in Canadian towns and cities of all sizes. *Preventive Medicine*, *77*, 174–180. https://doi.org/10.1016/j.ypmed.2015.05.011

Thomas, J., & Zeller, L. (2017). National walkability index user guide and methodology. *Environ. Prot. Agency: Washington, DC, USA*.

Thomas, K. M., Hesam Shariati, F., Hallum, S. H., & Kaczynski, A. T. (2025). Examining the Relationship Between Social Vulnerability and Sidewalk Access and Walkability Across a Large Southeastern U.S. City. *Environmental Justice*, 19394071251378221. https://doi.org/10.1177/19394071251378221

Twenge, J. M., Cooper, A. B., Joiner, T. E., Duffy, M. E., & Binau, S. G. (2019). Age, period, and cohort trends in mood disorder indicators and suicide-related outcomes in a nationally representative dataset, 2005–2017. *Journal of Abnormal Psychology*, *128*(3), 185.

US Census Bureau, South Carolina. (2020). *US Census Bureau QuickFacts: South Carolina*. https://www.census.gov/quickfacts/fact/table/SC/POP060220#POP060220

U.S. Department of Agriculture, Economic Research Service. (2025). U.S. Department of Agriculture, Economic Research Service. 2020 Rural-Urban Commuting Area Codes. https://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes

US Department of Agriculture, Economic Research Service [USDA ERS]. (2024). *USDA, ERS*. https://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes/documentation/

US EPA, O. (2021, May 17). *National Walkability Index User Guide and Methodology* [Reports and Assessments]. https://www.epa.gov/smartgrowth/national-walkability-index-user-guide-and-methodology

Van Cauwenberg, J., Van Holle, V., De Bourdeaudhuij, I., Van Dyck, D., & Deforche, B. (2016). Neighborhood walkability and health outcomes among older adults: The mediating role of physical activity. *Health & Place*, *37*, 16–25. https://doi.org/10.1016/j.healthplace.2015.11.003

Van Holle, V., Van Cauwenberg, J., Van Dyck, D., Deforche, B., Van de Weghe, N., & De Bourdeaudhuij, I. (2014). Relationship between neighborhood walkability and older adults' physical activity: Results from the Belgian Environmental Physical Activity Study in Seniors (BEPAS Seniors). *International Journal of Behavioral Nutrition and Physical Activity*, *11*, 1–9.

Wali, B. (2023). Interactive impacts of walkability, social vulnerability, & travel behavior on COVID-19 mortality: A hierarchical Bayesian spatial random parameter approach. *Sustainable Cities and Society*, *91*, 104454.

Wang, M. L., Narcisse, M., & McElfish, P. A. (2023). Higher walkability associated with increased physical activity and reduced obesity among United States adults. *Obesity*, *31*(2), 553–564. https://doi.org/10.1002/oby.23634

Watson, K. B., Whitfield, G. P., Thomas, J. V., Berrigan, D., Fulton, J. E., & Carlson, S. A. (2020). Associations between the national walkability index and walking among US adults—National Health Interview Survey, 2015. *Preventive Medicine*, *137*, 106122.

Wei, Y. D., Xiao, W., Wen, M., & Wei, R. (2016). Walkability, land use and physical activity. *Sustainability*, *8*(1), 65.

Westenhöfer, J., Nouri, E., Reschke, M. L., Seebach, F., & Buchcik, J. (2023). Walkability and urban built environments—A systematic review of health impact assessments (HIA). *BMC Public Health*, *23*(1), 1–19.

White, M. J., McClure, E., Killeen, J., Howard, J., Skinner, A. C., Spears, T., & Perrin, E. M. (2021). Changes in the recreational built environment and youth body mass index. *Academic Pediatrics*, *21*(1), 76–83.

Willey, J. Z., Moon, Y. P., Sacco, R. L., Greenlee, H., Diaz, K. M., Wright, C. B., Elkind, M. S., & Cheung, Y. K. (2017). Physical inactivity is a strong risk factor for stroke in the oldest old: Findings from a multi-ethnic population (the Northern Manhattan Study). *International Journal of Stroke*, *12*(2), 197–200. https://doi.org/10.1177/1747493016676614

Williams, T., Lakhani, A., & Spelten, E. (2022). Interventions to reduce loneliness and social isolation in rural settings: A mixed-methods review. *Journal of Rural Studies*, *90*, 76–92.

Yoon, H., Choi, K., & Jang, Y. (2017). The Role of Neighborhood Walkable Design and Walking Behavior in Mental Health (poster). *Journal of Transport & Health*, *7*, S9.

Zhu, X., Lu, Z., Yu, C.-Y., Lee, C., & Mann, G. (2013). Walkable communities: Impacts on residents' physical and social health. *World Health Design*, *6*(3), 68–75.